INVESTIGATION OF SELF-CONSOLIDATING CONCRETE

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ABSTRACT
Conventional concrete tends to present a problem with regard to adequate consolidation in thin sections or areas of congested reinforcement, which leads to a large volume of entrapped air voids and compromises the strength and durability of the concrete. Using self-consolidating concrete (SCC) can eliminate the problem, since it was designed to consolidate under its own mass.

This study examined several mixture designs in the laboratory; the goal was to create mixtures with desirable flow characteristics that did not require additional consolidation yet provided adequate compressive strength, low permeability, shrinkage control, and resistance to cycles of freezing and thawing. The results provided a foundation for determining if SCC could be produced on a commercial scale using locally available materials at two concrete plants. SCC from one plant was used in a field application for a small bridge in a residential area. The results showed that with tweaking of the mixture proportions, SCC can be produced successfully and provide many benefits to the transportation agencies and the construction industry.

INTRODUCTION

In response to the reduction in the skilled labor force in Japan's construction industry and the consequential reduction in the quality of construction, researchers at the University of Tokyo began developing self-consolidating concrete (SCC) in 1986 *(1)*.

Ozawa et al. *(2)* authored the first paper on SCC in 1989, and Ozawa and other colleagues *(3)* presented a paper on the same subject at an international conference on concrete held in Istanbul in 1992. The presentation accelerated international interest in SCC. In 1998, the first international workshop on SCC was held in Kochi, Japan. Through efforts by Ozawa and his colleagues, more intensive research thrived, especially in large construction companies in Asia. Hence, SCC was used in many structures including buildings, bridge towers, and bridge girders (*1*). Positive attributes of SCC include safety, reduced labor and construction time, and improved quality of finished product *(1,4,5)*.

SCC is different than conventional concrete in that it has a lower viscosity and, thus, a greater flow rate when pumped. As a consequence, the pumping pressure is lower, reducing wear and tear on pumps and the need for cranes to deliver concrete in buckets at the job site *(6)*.

To achieve a high flow rate and avoid obstruction by closely spaced reinforcing, SCC is designed with limits on the nominal maximum size (NMS) of the aggregate, the amount of aggregate, and aggregate grading. However, when the flow rate is high, the potential for segregation and loss of entrained air voids increases. These problems can be alleviated by designing a concrete with a high fine-to-coarse-aggregate ratio, a low water–cementitious material ratio (w/cm), good aggregate grading, and a high-range water-reducing admixture (HRWRA) *(7)*. Viscosity modifying admixtures (VMA) are also used to reduce the tendency for segregation and enhance the stability of the air-void system *(8,9)*.

An additional negative aspect of SCC is shrinkage. Since generally a large amount of fine material is used in the mixtures (particularly those without VMA) and the NMS is limited, the concrete typically has higher shrinkage. Increased shrinkage may result in more cracks in the restrained concrete elements, which can accelerate the deterioration of both the concrete and the reinforcing.

PURPOSE AND SCOPE

The purpose of this project was to develop and evaluate the properties of SCC made with locally available materials, including flow, segregation, strength, permeability, resistance to cycles of freezing and thawing, and drying shrinkage. SCC studies were conducted in the laboratory and the field, followed by a formal field application.

MATERIAL, PROPORTIONING, AND TESTING

Overview

The first phase of the project involved laboratory research at the Virginia Transportation Research Council, where a feasible mixture design was developed. The second phase involved determining if SCC could be manufactured in large quantities for field applications using locally available materials.

In both phases, the concrete was tested for flow rate in the freshly mixed state and for compressive strength, permeability, drying shrinkage, air voids, and freeze-thaw resistance in the hardened state.

Laboratory Phase

Materials

All mixtures contained Type II portland cement and Class F fly ash, which was added at 20 percent of the total cementitious material. The coarse aggregate was crushed granite gneiss with an NMS of 25 mm and was prepared by blending aggregates retained on the 19.0, 12.5, 9.5, and 4.75-mm sieves, each 25 percent by weight. The fine aggregate was natural sand. Several admixtures were included in the mixture: a saponified rosin air-entraining admixture (AEA) complying with the requirements of ASTM C 260; a lignin regular water-reducing admixture (WRA) complying with the requirements of ASTM C 494, Type A; and polycarboxylate HRWRA complying with the requirements of ASTM C 494, Type F.

Proportioning

Fifteen concrete mixtures were prepared in the laboratory using the three-factor central composite design method *(10)*. The method is basically a statistical cube design that determines the various mixture combinations where the cube has three axes for the amount of cementitious material, w/cm, and fraction of fine aggregate to total aggregate. A total of 15 points were selected on the cube, including points at the eight corners, center of the cube, and centers of the six faces. The chosen combinations of the three variables are given in Table 1. Three additional samples of Batch 7 and one extra sample of Batch 8 were made to evaluate additional properties such as drying shrinkage and the air-void system.

Freshly Mixed Concrete Testing

The air content (ASTM C 231) and unit weight (ASTM C 138) of the freshly mixed concrete were measured.

The consistency and workability were evaluated using the slump flow and the U-tube tests. Because of its ease of operation and portability, the slump flow test is the most widely used method for evaluating concrete consistency in the laboratory and at construction sites. In this test, the diameter of the concrete flowing out of the slump cone is a measure of flow, thus determining the consistency and cohesiveness of the concrete (*11*,*12*). Typical slump flow values tend to be around 650 mm (*6*, *13*). This study used a slump flow range of 585 to 685 mm to allow for a margin of error.

In the U-tube test, the testing apparatus is a U-shaped container where a vertical wall separates the two legs of the "U." This wall extends for most of the height of the container, except for the bottom, where three vertical reinforcing bars replace the wall. After SCC is poured up to the full height of one side of the tube, a vertical gate is raised such that the material flows past the reinforcing bars and rises in the other side of the container. The equilibrium height of the U-tube is 360 mm; SCC should rise to at least 90 percent of this equilibrium height (i.e., 325 mm) in order to be placed without additional consolidation in areas of dense reinforcement.

Rheological properties, yield stress and viscosity, were determined. Rheology is the science that deals with the flow of materials (*14*). If a shear force is applied, a velocity gradient is induced in a liquid. The velocity gradient is equal to the shear rate. The proportionality between the force and shear rate is the viscosity. The stress needed to initiate flow is known as the yield stress. Concrete typically behaves like a liquid modeled by the Bingham equation, which describes flow as a linear relationship between the shear rate and the shear stress (*14*). The viscosity is the slope in this relationship, and the intercept marks the yield stress. Rheometers measure the yield stress and the viscosity, such as the BTRHEOM rheometer used in this study. The BTRHEOM rheometer is a parallel plate rheometer, where the concrete is sheared between two plates. In this study, the two rheological parameters were calculated using the Bingham equation. Yield stress should be less than 400 Pa in order to have good flow, and the viscosity should be below 200 Pa·s for satisfactory pumping (*15*).

Hardened Concrete Testing

Most of the laboratory specimens for the hardened state tests were cast in molds without being consolidated; a few were vibrated for 5 seconds to determine if vibration improved the compressive strength. All of the samples were moist cured and then air dried. The samples were tested for compressive strength, permeability, shrinkage, freeze-thaw resistance, and air-void analysis, as summarized in Table 2.

For the air-void analysis, two samples were subjected to a linear traverse analysis (ASTM C 457). In this analysis, air bubbles less than 1 mm in diameter define spherical air-entrained bubbles and air bubbles greater than 1 mm in diameter are considered to be entrapped because of the lack of consolidation and extra water. Properly consolidated concrete should contain less than 2 percent of these larger bubbles (*16*). The spacing factor should be less than 0.20 mm, and the specific surface should be more than 24 mm^{-1} to provide sufficient resistance to freezing and thawing in a severe environment (*17*).

Field Phase

Materials and Proportions

During the field phase of this project, SCC mixtures were produced at a precast plant and a prestressing plant, designated as P1 and P2, respectively. The mixture proportions used at the two plants are provided in Tables 3 and 4. The acceptable range for the air content was 5.5 ± 1.5 percent. The various admixtures used complied with the appropriate specifications: both AEAs complied with the requirements of ASTM C 260; the WRA complied with the requirements of ASTM C 494, Type A; and the HRWRA complied with the requirements of ASTM C 494, Type F.

Testing

Batches from both plants were tested in the same manner as the laboratory batches; however, different consolidation and curing procedures were used for the compressive strength tests of the P2 samples. These samples were divided into three groups. The first group was rodded and moist cured. The second group was not rodded, but was moist cured. The third group was not rodded prior to being steam cured. To ensure self-consolidation, these specimens were compared to additional samples that were subjected to consolidation; rodding was the method of consolidation in the field. The strength and permeability tests of the consolidated samples provided a baseline for evaluating the need for consolidation. Freeze-thaw resistance was also determined in the field mixtures. Moist-cured beams were tested. One P1 specimen was subjected to linear traverse analysis.

The samples were also checked for concrete segregation during testing of the fresh SCC. The aggregate distribution and mortar halo around the spread in the slump flow test, as well as the lack of coarse aggregate in the top of the U-tube, indicated the extent of segregation within the concrete.

RESULTS AND DISCUSSION

Laboratory Phase

Freshly Mixed Concrete

The combined fine and coarse aggregate grading is given in Figure 1. Satisfactory SCC mixtures were accomplished with the laboratory gradings. The properties of the freshly mixed concrete and the observations of the behavior of the concrete are given in Table 5 for each batch. The slump flows ranged from 585 mm to 735 mm; approximately 75 percent of the batches fell within the specified range of 585 to 685 mm. Except for Batch 15, the batches reached the desired height of 325 mm in the U-tube test. In addition, all batches had viscosity values below 200 Pa·s and all batches except Batch 8 had yield stresses below 400 Pa, thus indicating that most mixtures could be pumped easily and had high flow past closely spaced reinforcement *(15)*. However, because of difficulties in entraining the desired amount of air; some air contents were outside the specified range. The wide range of air content was attributed to the large amount of HRWRA used in the mixtures. Large dosages of HRWRA can induce excessive paste fluidity, resulting in loss of air. This negative aspect can be controlled by the use of VMA *(9)*. Despite the difficulty in achieving all of the desired qualities, a number of mixture proportions from the laboratory phase had a sufficient air content while maintaining the desired flow characteristics for SCC.

The majority of the laboratory batches had difficulty maintaining the specified air content without having segregation problems. The aggregate distribution in the slump test, the mortar halo around the spread, and the lack of aggregates at the top of the U-tube clearly showed that segregation was an issue that must be watched closely. The 25-mm NMS coarse aggregate and low amount of material retained on 2.36-mm sieve and high amount of HRWRA may have made these concretes more prone to segregation and bleeding. Despite the number of designs that failed to comply with the specifications or did not have satisfactory flow characteristics, a number of mixture proportions proved to be viable candidates for SCC.

Hardened Concrete

Although the 15 specimens exhibited variability in the 28-day compressive strengths, all samples exceeded the minimum specified strength of 27.6 MPa, as shown in Table 6. The strengths of specimens were similar irrespective of the consolidation effort. No samples were made from batch 14 because of the extensive segregation in that mixture.

Table 6 also displays the results from permeability tests conducted in accordance with AASHTO T 277. These values were 23 to 78 percent below the specified maximum value of 2500 Coulombs. Although the vibrated samples had slightly higher values than the non-vibrated samples, the differences were within the expected variability.

Batches 7 and 8 were tested for shrinkage, with the results shown in Table 6. The values for both batches were below 400 microstrain at 28 days and 700 microstrain at 4 months, which are the maximum limits for satisfactory performance in bridge deck concretes (*18*).

Batches 7 and 8 were also subjected to linear traverse analysis. Large air voids (those with a diameter larger than 1 mm) made up less than 2 percent of the air in both batches, indicating adequate consolidation (see Table 7). Each had a total air content that was higher than the desired 8 percent maximum. Batch 7 had a spacing factor slightly above and Batch 8 below the 0.20-mm maximum, indicating satisfactory freeze-thaw resistance in a severe environment (*17*).

Table 8 summarizes the resistance to freezing and thawing for Batches 3, 5, and 6. The acceptance criteria at 300 cycles were weight loss of 7.0 percent or less, durability factor of 60 or greater, and surface rating less than or equal to 3. All three laboratory batches met the criteria.

Field Phase

Freshly Mixed Concrete

The plant mixtures had smaller aggregates than in the laboratory mixtures in order to maximize paste content and improve flow characteristics. For the P1 mixture, the slump flow values ranged from 572 to 660 mm, as shown in Table 9. The slump flow values for the P2 mixture were considerably lower, starting out at 483 mm for Batch 1 and increasing to 572 mm with the combination of WRA and HRWRA in Batch 2. Because of a significantly lower slump flow, no samples were made from only Batch 1. Although Batch 2 had a slump flow value below the specified minimum, the mixture was used to make specimens for the hardened state tests at P2. Table 9 also shows that the U-tube test values for some of the batches were below but close to the 325-mm maximum. There was no visible segregation or bleeding, and the air contents were satisfactory, ranging from 5.1 to 7.0 percent.

Hardened Concrete

Like the laboratory samples, 28-day strengths for the plant specimens exceeded the 27.6 MPa minimum and the permeability values were well below the 2500 Coulomb maximum. Table 10 shows that the P2 samples had similar compressive strengths regardless of whether the sample was rodded, thus indicating the SCC was well consolidated. As expected, moist-cured samples had lower 7-day strengths, but had higher 28-day strengths when compared to the steam cured specimens. Table 10 also shows that the shrinkage values varied from 420 to 495 microstrain, which were higher than the desired 400-microstrain. The higher shrinkage values result from the smaller NMS, smaller amount of coarse aggregate, and increased amount of water used, which increase paste content (*19*).

The P1 concretes had low freeze-thaw resistance, as seen in Table 8. All specimens had weight loss that was significantly higher than the acceptable value of 7 percent. Batches 1 and 3 had durability values less than the minimum acceptable value of 60, had surface ratings greater than the acceptable limit of 3, and failed to complete the 300-cycle test. On the other hand, the SCC made at P2 had desirable freeze-thaw resistance properties in all three categories of weight loss, durability, and surface rating.

Samples from P1, Batch 1, were subjected to linear traverse analysis. The larger bubbles accounted for only 0.54 percent of the air content, thus satisfying the 2 percent maximum, as shown in Table 7. Further, the 5.1 percent total air content in this batch was within the 4 to 8 percent range required for satisfactory performance. However, the spacing factor exceeded the 0.20-mm maximum required to resist the cycles of freezing and thawing in a severe environment *(17)*, and the specific surface was less than the minimum required value of 24 mm^{-1}. These results appear marginal at best and raise concerns about achieving the proper void system in SCC with high dosages of HRWRA.

Field Application

Results from laboratory and field testing indicated that SCC was feasible, which led to a field application involving an arch bridge in Fredericksburg, Virginia. This project was an excellent candidate for SCC because the arches are heavily reinforced, thin, curved sections that would be difficult to construct with conventional concrete.

The bridge carries traffic over a small creek in a residential area. A total of 25 precast arch segments were placed side by side to create a single 9.14-m span across the creek. Each segment is an ellipsoidal arch measuring 2.29 m wide and 254 mm thick, with an arc length of 13.72 m. The bridge has a total width of 57.51 m and a clearance above the creek of 3.81 m. The roadbed is supported by 9.14 m of soil filled vertically above the arch.

The cementitious material was a combination of Type III portland cement and slag, which was added at 35 percent of the total cementitious material. The coarse aggregate was crushed granite with an NMS of 19 mm; the fine aggregate was natural sand. Two admixtures were included in the design. One was a commercially available air-entraining admixture. The other was a polycarboxylate HRWRA.

During casting, each steel arch mold was placed on its side and SCC was poured at one end of the arch. The SCC spread from the point of pouring for an arc distance greater than 12.19 m without requiring manual labor. The concrete was delivered in buckets carrying 2.29 m^3 of concrete, with each load leveling itself and the subsequent load flowing over the previous one without leaving any marks. The surface of the arch units was very smooth.

To determine if settlement occurred after placement, SCC was cast in a 1.25-m-long tube and kept vertical while curing. After 1 week, the tube was cut in half longitudinally to determine the percentage of paste, the distribution of fine and coarse aggregate, and the air content in both the top 150 mm and bottom 150 mm of the tube. The percentages for the individual materials were similar in the top and the bottom, indicating lack of segregation.

The fact that no segregation occurred in the 1.25-m cylinder, and the concrete was easily poured into the arch molds, indicates that successful SCC is possible in a commercial process and on a larger production scale.

CONCLUSIONS

- SCC that flows into formwork and through reinforcement under the influence of its own weight can be made such that no external vibration is required.

- Although careful proportioning and batching are needed, SCC can be produced with locally available materials.

- SCC can have high compressive strength and low permeability for use in bridge structures.

- Concretes with a high slump flow are prone to segregation and bleeding. Tests should be conducted with the material used for a specific project to establish that the SCC flows sufficiently but will not segregate, bleed, or require additional consolidation.

- High drying shrinkage, improper air-void systems, and reduced freeze-thaw resistance can occur but are not necessarily intrinsic to SCC. Using the correct proportion of materials can mitigate these problems.

- To have a high slump flow without segregation, the amount of fine material should be increased by reducing the NMS, increasing the fine-aggregate-to-coarse-aggregate ratio, and increasing the amount of cementitious material. If such changes are not made, the use of a VMA may be necessary.

RECOMMENDATION

SCC is particularly applicable to thin sections and areas with dense reinforcement because of its high workability.

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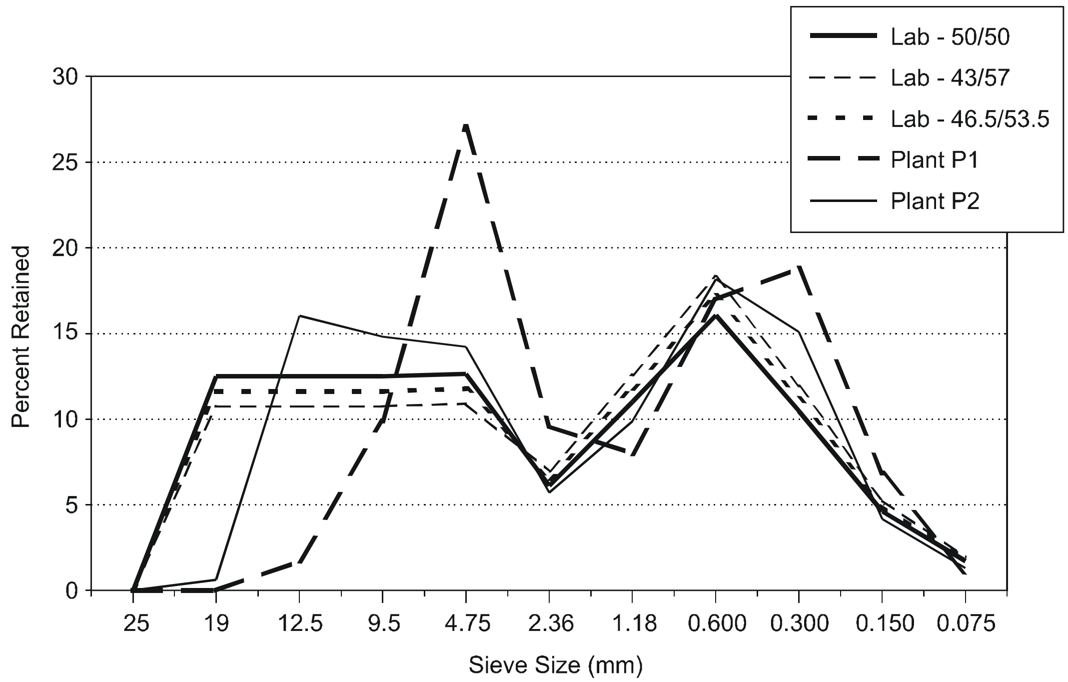

FIGURE 1 Aggregate grading for laboratory and field phases.

TABLE 1 Mixture Designs of Laboratory Concrete

Batch No.	Total Cementitous Material (kg)	w/cm	FA/TA
1	363	0.33	0.57
2	363	0.33	0.50
3	318	0.33	0.57
4	318	0.33	0.50
5	340	0.33	0.54
6	363	0.40	0.54
7	318	0.40	0.54
8	340	0.40	0.54
9	340	0.47	0.54
10	340	0.33	0.54
11	318	0.33	0.50
12	363	0.33	0.57
13	340	0.33	0.50
14	318	0.33	0.57
15	340	0.40	0.54

FA = fine aggregate, TA = total aggregate.

TABLE 2 Hardened Concrete Tests and Specifications

Tests	Specification	Age (d)	Size (mm)
Compressive strength	AASHTO T 22	[a]	100 x 200
Permeability	AASHTO T 277	28	50 x 100
Drying shrinkage	ASTM C 157	28	75 x 75 x 285
Freeze-thaw analysis	ASTM C 666	[b]	75 x 100 x 405
Air void analysis	ASTM C 457	28	100 x 200

[a]At 28 days for lab specimens and 1,7, and 28 days for field specimens.
[b]These specimens are moist cured for 2 weeks and then air dried at least 1 week before testing. The test water contained 2% NaCl.

TABLE 3 Mixture Proportions for Plant 1 Concrete

Material	Description	Amount
Cement	Type III	216 kg
Pozzolans	Natural, ASTM C 618, Class N	93 kg
Fine aggregate	Natural sand	631 kg
Coarse aggregate	Granite, 19 mm NMS	703 kg
Water	---	126 kg
AEA	Sodium-salt type soap	0.20 mL/kg
HRWRA	Polycarboxlyate	5.22 mL/kg

TABLE 4 Mixture Proportions for P2 Concrete

Material	Description	Amount
Cement	Type II/III	205 kg
Slag	40%, ASTM C 989, Grade 120	137 kg
Fine aggregate	Natural sand	704 kg
Coarse aggregate	Granite, 12.5 mm NMS	610 kg
Water	----	122 kg
Test 1 Admixtures		
AEA	Neutralized Vinsol resin	0.08 mL/kg
HRWRA	Polycarboxylate	7.82 mL/kg
Test 2 Admixtures		
AEA	Neutralized Vinsol resin	0.08 mL/kg
WRA	Sugar and lignin solution	9.13 mL/kg
HRWRA	Polycarboxylate	3.26 mL/kg

TABLE 5 Fresh Concrete Properties of Laboratory Mixes

Batch No.	Spread (mm)	U-Tube (mm)	Air (%)	Yield Stress (Pa)	Viscosity (Pa•s)	Observations
1	735	365	6.5	—	—	Sticky, segregation
2	735	355	—	—	—	Some segregation
3	660	350	11.7	21	151	Sticky, some segregation
4	710	375	—	—	—	Sticky, segregation
5	685	345	8.5	-64	64	Some segregation
6	710	350	2.7	-230	46	Good mix
7	660	345	7.6	276	52	Very good mix
8	660	345	7.8	470	53	OK
9	635	345	7.5	354	49	OK
10	685	345	5.5	189	38	OK
11	710	355	5.5	233	5	Good mix
12	585	355	0.5	—	—	Wet, some segregation
13	685	345	3.8	173	35	Segregation
14	710	330	2.0	—	—	Segregation
15	735	260	3.7	117	52	Segregation

TABLE 6 Hardened Concrete Properties of Laboratory Batches at 28 Days

	Strength (MPa)		Permeability (Coulombs)		Shrinkage (microstrain)		
Batch No.	No Vibration	Vibration (5 s)	No Vibration	Vibration (5 s)	28 day	4 mo	8 mo
1	36.3	37.0	—	—	—	—	—
2	39.9	—	—	—	—	—	—
3	41.0	—	1223	—	—	—	—
4	29.4	30.3	—	—	—	—	—
5	50.0	—	1295	—	—	—	—
6	46.1	—	992	—	—	—	—
7	37.1	35.7	—	—	—	—	—
7A	31.3	36.5	1015	1196	—	—	—
7B	43.8	42.0	1134	1325	—	—	—
7D	34.7	—	545	—	365	490	560
8	36.1	—	1726	2112	—	—	—
8A	42.0	—	429	—	380	520	590
9	37.2	—	—	—	—	—	—
10	40.3	—	—	—	—	—	—
11	32.9	—	—	—	—	—	—
12	37.9	—	1909	—	—	—	—
13	32.5	—	—	—	—	—	—
15	33.4	—	—	—	—	—	—

TABLE 7 Linear Traverse Analysis of Sample Batches

Location	Batch No.	Air Content (%) < 1 mm	Air Content (%) > 1 mm	Air Content (%) Total	Specific Surface (mm^{-1})	Spacing Factor (mm)
Laboratory	7	7.1	1.0	8.1	18.3	0.2097
	8	9.8	0.2	10.0	22.2	0.1491
Plant 1	1	4.6	0.5	5.1	20.4	0.2517

TABLE 8 Freeze-Thaw Analysis of Sample Batches

Location	Batch No.	Weight Loss (%)	Durabilty Factor	Surface Rating
Laboratory	3	0.7	106	0.9
	5	1.0	108	0.8
	6	2.3	96	1.2
Plant 1	1	16.5	43	3.4
	2	12.0	91	2.6
	3	29.9	43	4.7
Plant 2	2 moist cured	4.9	113	1.4

TABLE 9 Fresh Concrete Properties in Field Phase

Plant	Batch No.	Spread (mm)	U-Tube (mm)	Air (%)	Unit Weight (kg/m^3) [a]	[b]	[c]
1	1	572	305	5.1	—	—	—
	2	610	292	7.0	21.4	22.3	22.1
	3	660	330	5.2	22.0	22.7	22.5
2	1	483	222	6.4	—	22.4	23.1
	2	572	318	6.2	—	22.6	22.7

[a]Measured at the freshly mixed state in accordance with ASTM C 138.
[b]Using the information on mixture design, a unit weight was calculated (2313 kg/m^3 for Plant 1 and 2323 kg/m^3 for Plant 2). Then the unit weight was corrected for the air content measured and displayed in the column.
[c]Calculated from hardened cylinders.

TABLE 10 Hardened Concrete Properties of Field Phase

Plant	Batch No.	Permeability (Coulomb)	Strength (MPa)			Shrinkage (microstrain)		
			1 d	7 d	28 d	28 d	4 mo	8 mo
1	1 not rodded	786	19.9	29.2	39.6	420	590	610
	1 rodded	—	—	—	38.3	—	—	—
	2 not rodded	923	16.6	24.4	34.3	415	201	605
	2 rodded	—	—	—	34.3	—	—	—
	3 not rodded	1145	16.5	26.2	35.4	465	720	720
2	Moist cured, rodded	—	32.7	33.3	52.7	470	650	725
	Moist cured, not rodded	—	32.8	33.0	53.8	490	650	730
	Steam cured	1624	—	41.4	46.3	495	655	695